Deceleration in the Expansion of SN1993J

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ABSTRACT

A rarity among supernova, SN 1993J in M81 can be studied with high spatial resolution. Its radio power and distance permit VLBI observations to monitor the expansion of its angular structure. This radio structure was previously revealed to be shell-like and to be undergoing a self-similar expansion at a constant rate. From VLBI observations at the wavelengths of 3.6 and 6 cm in the period 6 to 42 months after explosion, we have discovered that the expansion is decelerating. Our measurement of this deceleration yields estimates of the density profiles of the supernova ejecta and circumstellar material in standard supernova explosion models.

Subject headings: supernovae:individual (SN 1993J); circumstellar matter galaxies:individual (NGC3031, M81); techniques: interferometric; radio continuum: stars;

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1. INTRODUCTION

Supernova SN 1993J in M81 discovered by Francisco García of Lugo , Spain (Ripero and García 1993) is a type IIb supernova (SN) whose red giant progenitor probably had a mass of 12-16 $M_\odot$ while on the main sequence; at the time of the explosion, 3-5 $M_\odot$ likely remained in the He core and $\lesssim$1 $M_\odot$ in the He/H envelope (Filippenko et al. 1993, Shigeyama et al. 1994, Woosley et al. 1994, Iwamoto et al. 1997). The first maximum in the supernova optical light curve has been attributed to shock heating of the thin envelope and the second to radioactive decay of ^{56}Co (Nomoto et al. 1993, Shigeyama et al. 1994, Woosley et al. 1994). Modelling of the X-ray emission (Suzuki and Nomoto 1995) also implies a relatively low mass envelope due to interaction with a binary companion (Nomoto et al. 1993, Woosley et al. 1994).

The standard circumstellar interaction model –hereafter standard model or SM– for radio supernovae (Chevalier 1996 and references therein) suggests that the radio emission arises from a shocked region between the supernova ejecta and the circumstellar material (CSM) that results from the wind of the SN's progenitor star. More specifically, the SM considers SN ejecta with steep density profiles ($\rho_{ej} \propto r^{-n}$) shocked by a reverse shock that moves inwards from the contact surface and a CSM with density profile $\rho_{csm} \propto r^{-s}$ shocked by a forward shock that moves outwards from the contact surface (s=2 corresponds to a steady wind). For n>5, self-similar solutions are possible (Chevalier 1982a); the radii of the discontinuity surface, forward shock and reverse shock are then related and all evolve in time with a power law R $\propto t^m$ (t, time after explosion), where m=$(n-3)/(n-s)$.

SN 1993J is the closest SN that is both young and radio bright (Weiler et al. 1996) and hence offers a unique opportunity for the study of its radio structure and the test of radio supernova models (Chevalier 1982a, Suzuki and Nomoto 1995). Marcaide et al. (1995a) found the radio structure to be shell-like. Multiwavelength radio light curves and high resolution radio images of SN 1993J (Van Dyk et al. 1994, Marcaide et al. 1995b, respectively) established the self-similar nature of the expansion.

The technique of VLBI can, in principle, determine m directly by simply observing the angular growth rate of the supernova. Bartel et al. (1994) and Marcaide et al. (1995b) found that m=1 was compatible with their results to within their respective uncertainties. In this paper, we present VLBI results for λ6 cm through October 1996 (42 months after explosion), combined with those already published for λ3.6 cm (Marcaide et al. 1995b), to estimate the deceleration in the supernova expansion and to infer the density profiles of the

supernova ejecta and CSM.

2. OBSERVATIONS AND RESULTS

In our λ6 cm VLBI observations of SN 1993J, global arrays formed by the phased-VLA, antennas in Effelsberg (Germany) and Medicina and Noto (Italy), and various subsets of the 10-antenna VLBA were used. For the first 3 epochs (see Table 1) MkIIIA instrumentation and a recording bandwidth of 56 MHz were used and the data were correlated at the Max Planck Institut fuer Radioastronomie in Bonn, Germany. For the last 4 epochs, VLBA instrumentation and a recording bandwidth of 64 MHz were used and the data were correlated at the National Radio Astronomy Observatory in Socorro, NM. The sources 0917+624, 0954+658, and the nucleus of M81 were observed as calibrators, the first two as amplitude calibrators and the nucleus of M81 both as an amplitude calibrator and, for epochs later than June 1996, as a phase calibrator. In all cases we analyzed the data using DIFMAP (Shepherd et al. 1994) in a standard way using measured system temperatures and either antenna-temperature measurements or gain-curve information from each antenna as initial calibration. For 0917+624, we obtained brightness maps using self-calibration and the source structure determined by Standke et al. (1996) as an initial model. The calibration correction factors obtained with the self-calibration of 0917+624 were then applied to calibrate the data of SN 1993J and the nucleus of M81. A similar iteration was carried out using the very compact, VLBI nucleus of M81 and those new calibration corrections were also applied to the calibration of the data of SN 1993J.

We constructed a map of SN 1993J for each epoch, using a standard process. We used each of the following initial models: a point source, a scaled model from a previous epoch, and a super-symmetrized scaled model (obtained by rotating the scaled model by $ndeg$, such that $360/ndeg$ is an integer n, then rotating by $2ndeg$, etc., adding all the rotated models, and rescaling the resulting flux density distribution). The total flux density in each map was checked against the light curve of Van Dyk et al. (1994) and recent VLA measurements. Agreement was found to be better than 5% except for two epochs where the discrepancy was as large as 8%. The resultant maps were virtually independent of the starting model and are shown in Plate 1. For this display circular convolving beams with sizes proportional to the number of days elapsed since the explosion were used (see Table 1). Such beams permit both a better visualization of the self-similar expansion (the radio structure remains similar except for a scale factor) and a better estimate of the deceleration parameter m. In Figure

1 we show the map from the latest epoch (22 October 1996) convolved with an elliptical gaussian beam whose half-power size is given by the corresponding size of the main lobe of the interferometric beam from that epoch, so that the details of the source structure are more visible than in Plate 1.

Each map of SN 1993J shows a shell-like radio source. The inferred source size depends on how the map is constructed and how it is measured. Because of the non point-like size of the VLBI beam, a positive bias is introduced in the size estimate of each map: The estimated size is larger than the true size. The fractional bias will systematically decrease for a source increasing in size if the same beam applies for all observations. If uncorrected, this bias introduces a bias in the estimate of the growth rate of the source. However, for self-similar expansion, as here, a method can be found (see below) such that the bias can be kept approximately constant with source growth and hence does not significantly affect the estimate of the deceleration parameter.

If the shape of the expanding source does not change and the expansion rate is nearly constant we can largely avoid introducing a spurious deceleration by using a beam size proportional to the number of days between the explosion and the epoch of the source map. Plate 1 (see also Marcaide et al. 1995b) shows that we are indeed in such a situation. An alternate mapping procedure based on using beam sizes proportional to actual source sizes would produce, in principle, a (slight) improvement. In practice, other map errors would probably prevent any discernible improvement.

To use convolving beams as similar as feasible to the VLBI beams and still use the above-described procedure, we chose a range of convolving beam sizes so that each is always within a factor of two of its VLBI beam. For the early epochs, we therefore chose small convolving beams and overresolved our images by almost a factor of two; for the late epochs, we chose large convolving beams and degraded the map resolution by almost a factor of two. We also applied the same criteria to the λ3.6 cm maps (Marcaide et al. 1995b).

In Table 1, we list the measured outer radius of the supernova shell for each epoch of observation and plot the results in Figure 2. Each such size was estimated by the average of the source diameter at the 50% contour level of the map from eight uniformly-spread azimuthal cuts through the map. The standard errors quoted in Table 1 result from adding in quadrature an error twice as large as the measurement error in the diameters and an error in determining the 50% contour level location due to map noise and beam size limitations. Using R $\propto t^m$ for the λ6 cm data yields m=0.89$\pm$0.03; combining the λ3.6 and λ6 cm data

gives m=0.86±0.02. Figure 2 shows only the latter result. The reduced chi-square of the model fit is 0.9; the quoted error has been scaled to correspond to a reduced chi-square of unity. In contrast, a fit of a straight line (m=1) to the data gives a reduced chi-square of 6.0.

We find, too, that the better the calibration and the more VLBI observations at a given epoch, the more spherical and the smoother the resultant image. Thus, some of the small emission asymmetries in the images may be artifacts.

3. DISCUSSION

Our maps give no indication of any structures developing in the shell by the action of either Raleigh-Taylor instabilities (Chevalier and Blondin 1995) or interaction with the CSM. There is also no evidence of any departure from circularity as suggested by some authors to explain the action of a putative binary companion. We also do not see any emission above $\sim$0.5 mJy from any compact source at the center of the structure (i.e., a pulsar as suggested by Woosley et al. (1994) and Shigeyama et al. (1994)).

Within the framework of self-similar models, measurement of the time dependence of the attenuation of the supernova radio emission due to the circumstellar plasma allows us to estimate the exponent of a power law representation of the density profile of the CSM: for free-free absorption as commonly invoked in radio supernova models (Weiler et al. 1996 and references therein), the opacity, τ, is proportional to the density squared integrated along the line of sight. Given a supernova radius R $\propto t^m$ and $\rho_{csm} \propto r^{-s}$, then $\tau \propto t^{2m(-s+0.5)}$. Van Dyk et al. (1994) found $\tau \propto t^{\delta}$ with δ=$-1.99^{+0.38}_{-0.16}$ for the homogeneous component of the CSM. Combining this result with m=0.86±0.02, we obtain s=$1.66^{+0.12}_{-0.25}$. This value is lower than the s=2 in the SM for a constant stellar wind, but very close to the value s=1.7 given by Fransson et al. (1996) to explain the X-ray emission (Zimmermann et al. 1994). Van Dyk et al. (1994) also obtain a similar time dependence for the attenuation of a clumpy medium and hence argue that the clumpy component is spatially distributed in the same way as the homogeneous component. Houck and Fransson (1996) also argue in favor of a clumpy medium based on optical line profiles. Suzuki and Nomoto (1995) postulate CSM with homogeneous and clumpy components to explain X-ray data, but they consider two regions: (1) An inner homogeneous region with a density profile described by s=1.7 out to radii smaller than $\sim 5{\times}10^{15}$cm and (2) an outer clumpy region with density profile described

by s=3 for the interclump medium at larger radii. Such a model of the CSM allows Suzuki and Nomoto (1995) to fit their model to all of the available X-ray data. Specifically, the s=3 clumpy medium is needed to account for the hard X-rays and for part of the Hα emission. The supernova explosion model of Suzuki and Nomoto (1995) , consisting of ejecta and a clumpy CSM as described above, is very different from self-similar models (Chevalier 1982b).

The self-similar case with m=0.86 and s=1.66 gives an ejecta density profile of $n=11.2^{+3.5}_{-1.8}$. These values correspond to steep profiles, indeed much steeper than the profiles of white dwarfs (n=7), but less steep than those suggested by Baron et al. (1995) from spectral analyses or those used by Suzuki and Nomoto (1995) . In the SM for values n=11.2 and s=1.66, the reverse shock radius is $\sim$2% smaller, and the forward shock radius $\sim$20% larger, than the radius of the contact surface between shocked supernova ejecta and shocked CSM (Chevalier 1982b).

Marcaide et al. (1995b) estimate that the width of the radio shell is about 0.3 times the size of the outer radius (or, equivalently, about 40% of the inner radius). These authors also estimate expansion speeds $\sim$ 15,000 km s^{-1} which are compatible with the largest velocities ($\sim$ 11,000 km s^{-1}) measured in Hα (Filippenko et al. 1994, Patat et al. 1995) if (i) the Hα emission originates in the vicinity of the reverse shock, (ii) a homologous expansion is assumed in the ejecta and shocked regions, and (iii) the shock shell is about twice as large as predicted in the SM . In an attempt to reconcile the SM and the observational results, Houck and Fransson (1996) suggest that clumpy ejecta and/or CSM can broaden the shell. On the other hand, the region of the ejecta shocked by the reverse shock in the model of Suzuki and Nomoto (1995) is even larger than that of the CSM shocked by the forward shock. However, the maximum speeds of the radio outer shell and of the region of Hα emission in the model of Suzuki and Nomoto (1995) match those observed very well, although the density and velocity profiles in the shell are very different from those of the standard model.

If we consider only VLBI results from epochs more than 500 days after the explosion, we obtain m=0.89$\pm$0.03 and $s=1.68^{+0.10}_{-0.27}$. However, such an age range is in the region in which the Suzuki and Nomoto (1995) model suggests s=3.0. A contradiction is apparent and our results therefore argue against their model. Our estimate of s based on that of m is not dependent on a given explosion model but is a determination from the time dependence of the opacity due to an external medium (Weiler et al. 1986,Van Dyk et al. 1994). Furthermore, such time dependence of the opacity has not changed between days 200 and 1000 (Van Dyk, priv. comm.).

If the physical picture of the radio and Hα emission in the SM were correct, the $\sim$15% decrease in expansion speed measured by VLBI between months 12 and 42 after explosion should be observable in the Hα emission. On the other hand, if the model of Suzuki and Nomoto (1995) were correct, a decrease in the maximum speed of Hα would not be expected.

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Plate 1. Sequences of radio images of supernova SN 1993J at λ6 cm placed at vertical positions proportional to number of days elapsed since explosion. The images clearly show a self-similar expansion. The CLEAN components have been convolved with circular beams whose radii are proportional to the number of days elapsed since explosion (see text). The beam sizes have been chosen so as to be within a factor of 2 of that of the VLBI beam for each observation. Each image in the sequence at left has an independent color-coded brightness scale. In the sequence at right the temperature scale is the same for all the images (maximum brightness temperature 8.88 mJy/beam).

Fig. 1.— Map at λ6 cm of SN 1993J from 22 October 1996, 1304 days after explosion. The maximum brightness is 2.48 mJy/beam. The elliptical gaussian beam used in the convolution to obtain this CLEAN map is shown in the lower left and has FWHM of 1.18 $\times$ 0.96 *mas* with the major axis along position angle 5°.

Fig. 2.— Angular radius of SN 1993J vs. days after explosion. The continuous line results from a fit of R $\propto t^m$ (t, time after explosion) to all the data. The value of m obtained is 0.86$\pm$0.02. For comparison, we show a straight line fit (m=1) to all the data as a dashed line (see text). The λ3.6 cm data come from Marcaide et al. 1995b.

Table 1. SN 1993J Sizes[1]

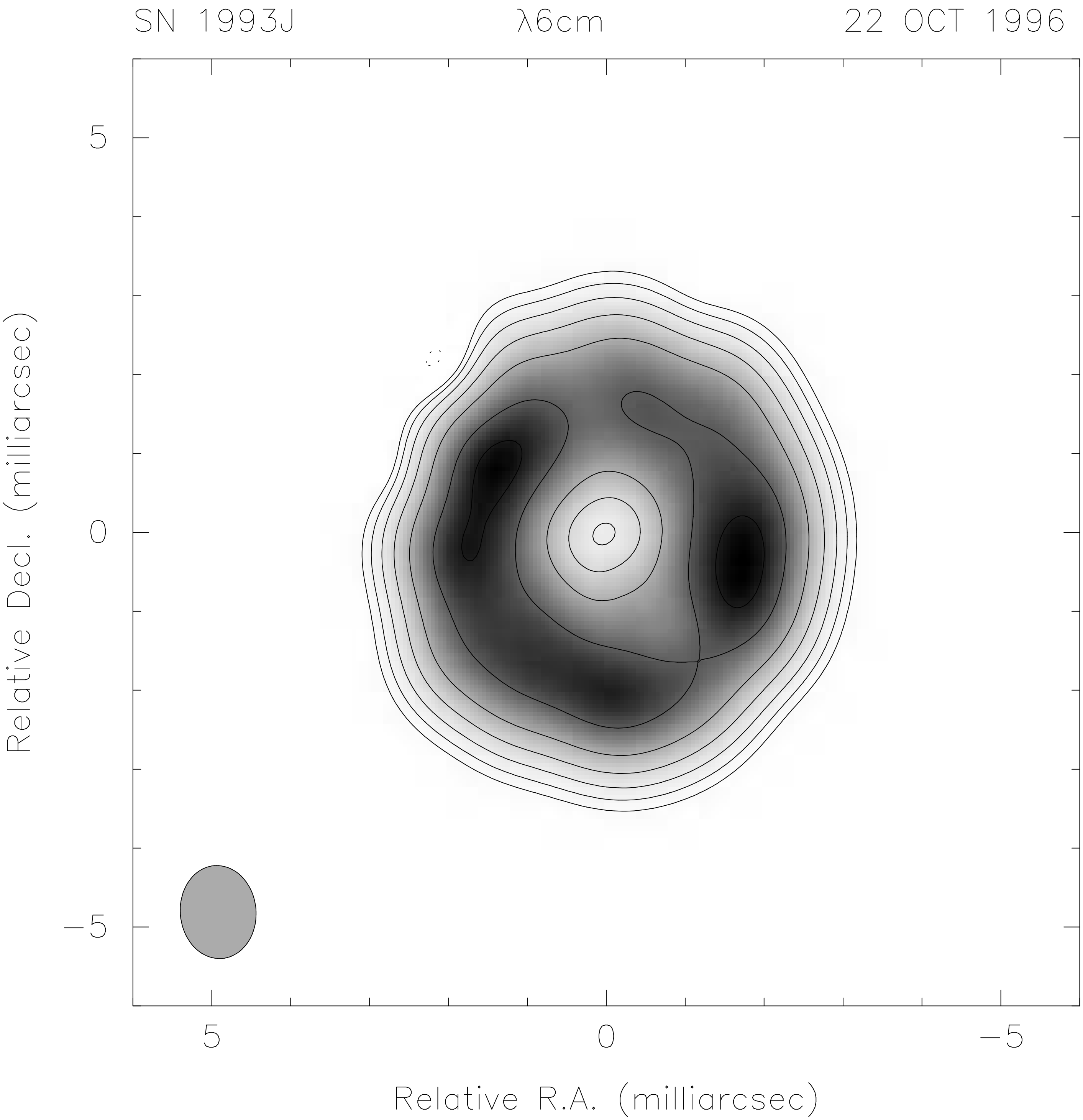
Date of observation	Age (days)	λ (cm)	Flux density[2] (mJy)	VLBI Beam[3] (mas)	Convolution Beam[4] (mas)	Shell outer radius[4] (μarcsec)
26-SEP-93	182	3.6	78.5	0.55×0.46 (13.6°)	0.26	464±90
22-NOV-93	239	3.6	57.3	0.52×0.45 (0.7°)	0.34	612±22
20-FEB-94	330	3.6	51.0	0.53×0.44 (6.5°)	0.46	824±90
29-MAY-94	427	3.6	41.5	0.61×0.52 (25.8°)	0.60	1071±28
20-SEP-94	541	6	53.4	0.99×0.82 (-47.2°)	0.76	1202±30
23-FEB-95	697	6	44.3	1.11×0.77 (17.2°)	0.98	1567±33
11-MAY-95	774	6	41.8	1.22×0.88 (18.0°)	1.09	1701±39
01-OCT-95	917	6	32.2	1.57×1.24 (-27.0°)	1.29	2026±55
28-MAR-96	1096	6	31.3	1.58×1.23 (-58.0°)	1.54	2301±72
17-JUN-96	1177	6	26.5	1.37×1.11 (30.2°)	1.65	2414±102
22-OCT-96	1304	6	26.1	1.20×0.97 (-6.1°)	1.83	2639±100

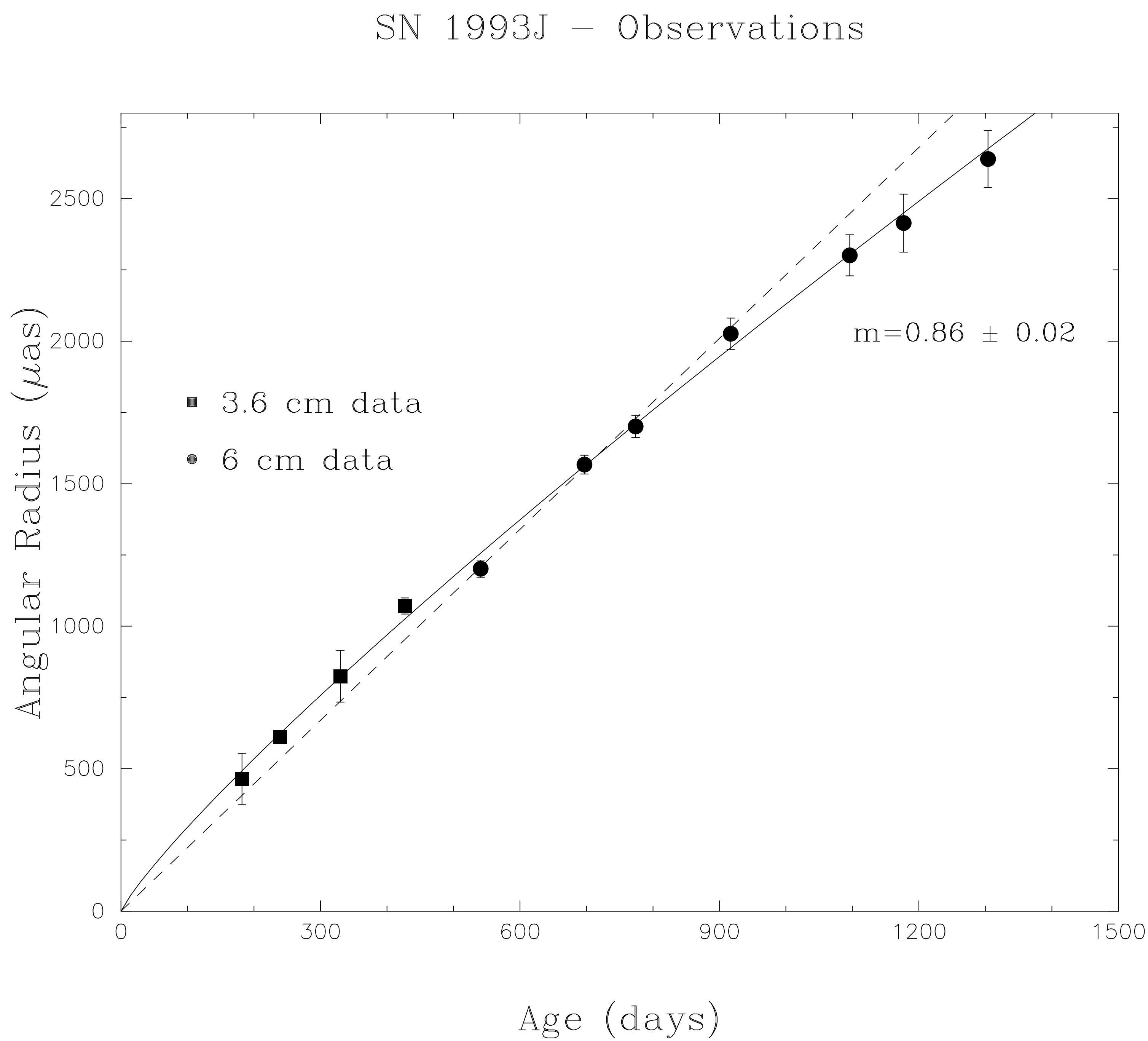
[1]The λ3.6 cm observations were reported by Marcaide et al. (1995b) but the data have been reanalyzed and the shell outer radius reestimated in a way similar to that used for the λ6 cm data, as described in the text.

[2]Total flux density used for mapping.

[3]Major axis × minor axis (position angle) of elliptical gaussian beam.

[4]As explained in text. Quoted errors are estimated one standard deviations.


SN 1993J
λ6cm
22 OCT 1996
5
0
−5
Relative Decl. (milliarcsec)
Relative R.A. (milliarcsec)


SN 1993J – Observations
3.6 cm data
6 cm data
m=0.86 ± 0.02
Angular Radius (μas)
Age (days)
0
500
1000
1500
2000
2500
0
300
600
900
1200
1500